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Utility Interface Issues

Over the last decade, the electric machine industry has been placing more emphasis on variable- and adjustable-speed operations. Developments in power electronics made it possible to achieve these goals. However, this technology produces pollution to the utility grid and raises power quality issues. This chapter describes recent harmonic regulations imposed on power electronic equipments and systems. Merits and demerits of poor power quality drives are also explained. As a solution, various power factor correction (PFC) techniques are introduced for advanced motor drives. Different techniques for active and passive filters, special drive topologies for PFC, and harmonic injection are explained in detail.

Most traditional motor drives are fixed-speed drives. Recent advancements in the power electronic industry have encouraged machine manufacturers to start developing systems for adjustable-or variable-speed/frequency drives. Among the reasons for adopting adjustable-speed drives (ASDs) are better overall performance, improved efficiency, and reduced hardware complexity. Power

electronics is used as an interface between the utility and motor. In other words, the machine is driven by a power electronic interface rather than the utility supply. The obvious reason is to achieve a variable form of supply, which is not available from the utility. By adjusting this variable supply, machine performance can be optimized. A typical advanced electric motor drive architecture is shown in Fig. 10.1. In the figure, the utility supply can be single phase or three phase. The machine can be single phase, three phase, or even multiphase, depending on the performance requirement. The power electronic system is designed in a way such that the machine can be optimized for its own performance independent of the available supply. Sensors can be Hall-effect or it is also possible to achieve sensorless drives.

The increased use of ASDs in power systems have led to a major problem for power quality. ASDs along with their power electronic drives appear as nonlinear loads to the utility grid or power system. In general, any power electronic driven system imposes power quality

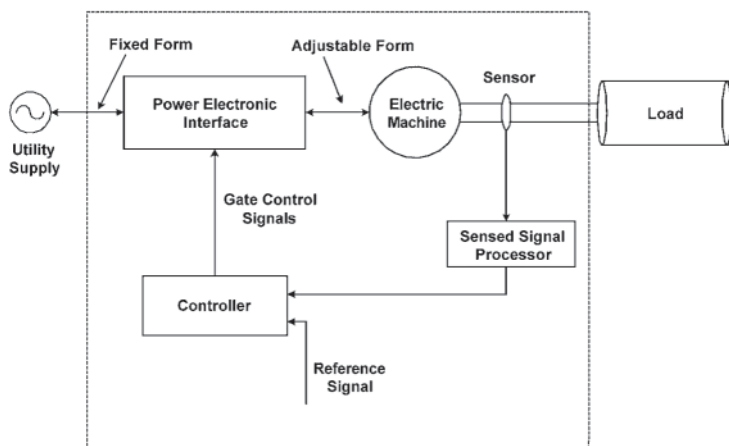


FIGURE 10.1 Advanced electric motor drive architecture.

issues, i.e., power factor deterioration and harmonic distortion. The solution to these problems also resides in power electronics. Figure 10.2 shows the input current of a typical ASD. The harmonics of orders 5 and 7 are considerably high. Any electric motor drive system can be simplified, as shown in Fig. 10.3.

If the load is linear or the machine is directly connected to the mains, the supply voltage and current waveforms are sinusoidal and the power factor is given as follows:

$$\cos\Phi = \frac{V_s}{I_s}$$

However, advanced electric motor drives usually consist of a diode bridge rectifier followed by a bulk capacitor and the power processing stage. The bulk capacitor is used to smooth the output voltage

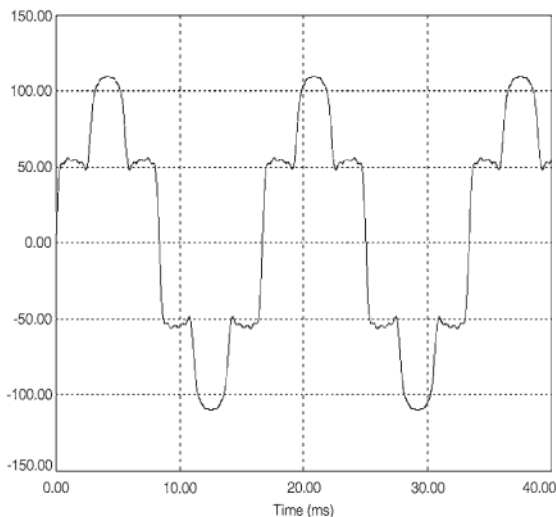


FIGURE 10.2 Input current of a typical ASD.

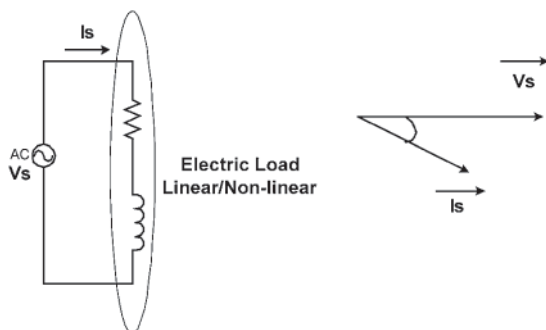


FIGURE 10.3 Simplified electric motor drive system.

waveform. The diode network and the capacitor draw current from the mains only when the instantaneous mains voltage is greater than the capacitor voltage. This results in a nonsinusoidal supply current waveform. In this case, the power factor is not given by the above simple equation. Now the power factor is defined as

$$\text{PF} = \frac{\text{DPF}}{\sqrt{1 + \text{THD}^2}}$$

where DPF is the displacement power factor and THD is the total harmonic distortion. DPF and THD are defined as follows:

$$\text{DPF} = \cos\phi_1 = \frac{V_s}{I_{s1}}$$

$$\text{THD} = \frac{I_{\text{distortion}}}{I_{s1}}$$

where I_{s1} is the fundamental component of the supply current. Since the capacitor is chosen for a certain hold-up time, its time constant is much greater than the frequency of the mains. This implies that the instantaneous mains voltage is greater than the capacitor voltage only for very short periods of time (charging time of capacitor). During

this time the capacitor must charge fully. Therefore, large pulses of current are drawn from the line over very short periods of time. This is true of all rectified AC sine wave signals with capacitive filtering. This causes the following problems:

- Creation of harmonics and electromagnetic interference (EMI)
- High losses
- Required overdimensioning of parts
- Reduced maximum power capability from the line

Power factor correction makes the load look more like a resistive element than would be the case without PFC. Modern PFC circuits can achieve power factors very near to unity. PFC circuits have the following advantages:

- Better source efficiency
- Overall lower power installation cost
- Lower conducted EMI
- Reduced peak current levels
- Act as filters for the conducted EMI
- Make possible common input filtering for paralleled supplies because the loads all appear to be resistive
- Better chance of agency approval

However, PFC circuits have one or more of the following disadvantages:

- Introduce greater complexity into the design
- Have more parts, adversely affecting reliability and cost
- Generation of EMI and radiofrequency interference (RFI) requires extra filtering, making the input filter more complex and more expensive
- Higher system cost

Harmonic standards developed by IEEE and IEC are enforced in many parts of the world including Europe. Therefore, PFCs have attracted a lot of attention in the power electronic industry. In most applications, it is not difficult to meet these standards; however, the

most economic choices are still being developed. IEEE and international harmonic standards can be grouped into three main categories:

1. Customer system limits:
 - IEEE 519-1992
 - IEC 1000-2-2 (compatibility levels)
 - IEC 1000-3-6
2. Equipment limits:
 - IEC 1000-3-2
 - IEC 1000-3-4
 - New task force in IEEE (harmonic limits for single-phase loads)
3. How to measure harmonics
 - IEC 1000-4-7

The IEC 1000 series deals with electromagnetic compliance. Part 3 sets limits and Series 2 addresses limiting harmonic current emission for equipment input current less than or equal to 16 A. IEC 1000-3-4 not only deals with individual equipment, but also sets limits for the whole system installation. Both single-phase and three-phase harmonic limits are addressed in this section of the regulation. On the other hand, IEEE standard 519 sets limits of harmonic voltage and current at the point of common coupling (PCC). The philosophy behind this standard is to prevent harmonic currents traveling back to the power system and affecting other customers.

10.1 ASD EXAMPLE

As an example, a C-dump converter for an advanced switched reluctance motor (SRM) drive is investigated. The SRM cannot be operated by directly connecting to the mains. A power electronic interface is absolutely necessary for running it optimally. Various power electronic topologies have been proposed. C-dump converter topology is one of the popular topologies to drive SRMs. As this topology contains maximum number of passive elements and complexity, it is chosen to verify the PFC function for advanced drives

as a worst-case scenario. A power stage diagram and operating modes circuit reductions are shown in Figs. 10.4 and 10.5.

Three inductors grouped together represent three phases of the machine. The C-dump converter is operated in such a way that the required phase is energized and de-energized at required instances, i.e., aligned and unaligned positions of the rotor. Both hysteresis current control and PWM control are possible. Performance of the PFC circuit remains the same in all operating conditions. Even with different drives of different machines, this general PFC approach is equally effective.

The switches are turned on when the rotor is at the unaligned position, and they should not be conducting after the rotor phase passes the aligned position with the stator. There are various modes possible depending on particular applications. Here, when switches are turned on, the phase inductor and dump inductor store energy, and when the switches are turned off, both of them release the energy.

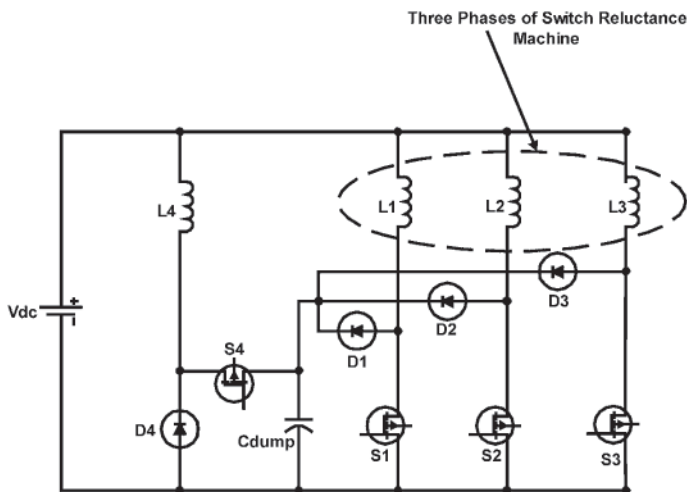


FIGURE 10.4 SRM drive with C-dump converter.

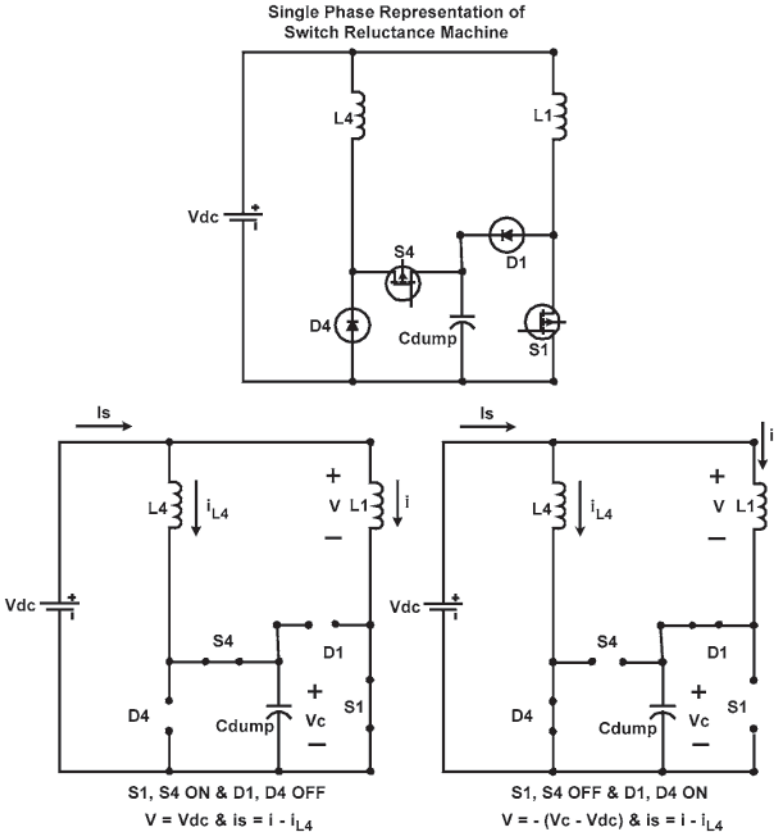


FIGURE 10.5 Single-phase power stage and operating state diagrams of C-dump SRM drive.

The dump capacitor charges in a half cycle and discharges in another half cycle. The voltage level of this capacitor should be higher than the DC link voltage. [Figure 10.6](#) shows the phase voltage and current waveforms when the drive is operated with the DC supply.

However, this is not the case with the home or commercial applications of many drive systems. Those drive systems pass through

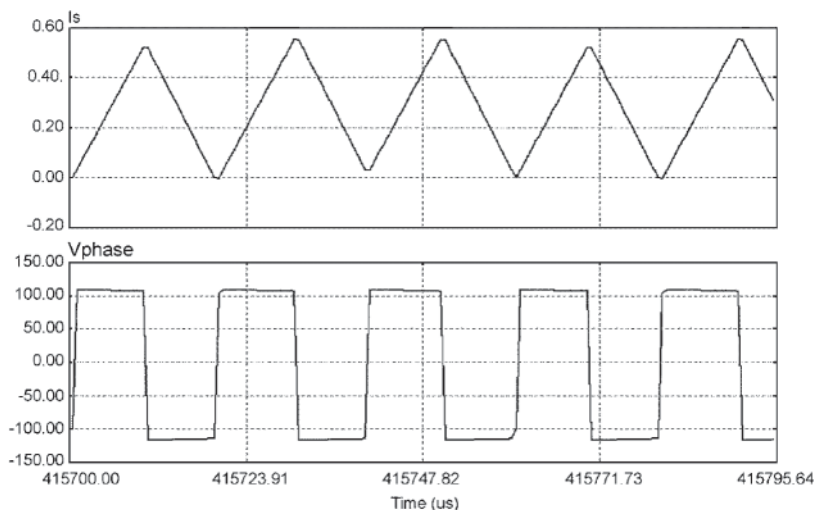


FIGURE 10.6 Phase current and voltage of SRM with DC supply at the front end.

one or more power conversion stages. In case of advanced DC drive systems, the AC supply of the utility is usually converted using a simple diode bridge rectifier (DBR). As mentioned before, when only a DBR is connected between the drive and utility, the smoothing capacitor gets charged and discharged during the high line periods (short time intervals), and high current spikes occur. This deteriorates both power factor and overall system performance. Figure 10.7 explains the power stage of such uncontrolled DC link. Waveforms are depicted in Fig. 10.8. From the supply voltage and current waveforms shown in Fig. 10.8, it is clear that high distortion occurs on the supply side.

The effects of poor power factor are illustrated in this section. This has encouraged various organization to introduce standards for allowable harmonics and minimum power factors of power electronic systems. By doing so, power quality of the overall power system can be improved by a considerable amount. In addition, material cost

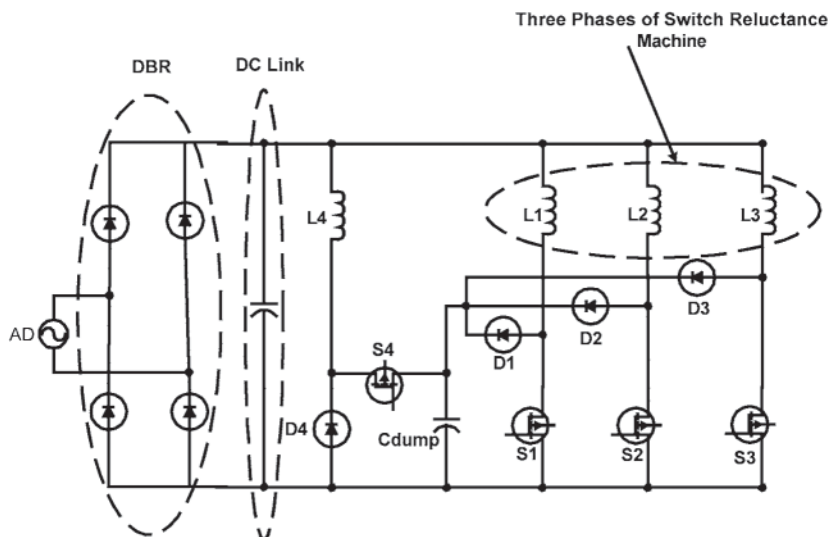


FIGURE 10.7 SRM drive with DBR at its front end as uncontrolled DC link.

saving can be realized in home appliance systems. The next section discusses different basic methods of power factor correction.

10.2 POWER FACTOR CORRECTION METHODS

Depending on the circuit elements employed in the power factor correction technique, power factor correction can be subdivided into passive PFC, active PFC, and harmonic injection. Some time-special topologies are to be employed to reduce the component count. All of these techniques are explained here with simulation examples.

Passive PFC This correction method is the simplest and is employed by most power processor circuits, such as switching power supplies and advanced motor drives. It is very effective in lowering and limiting

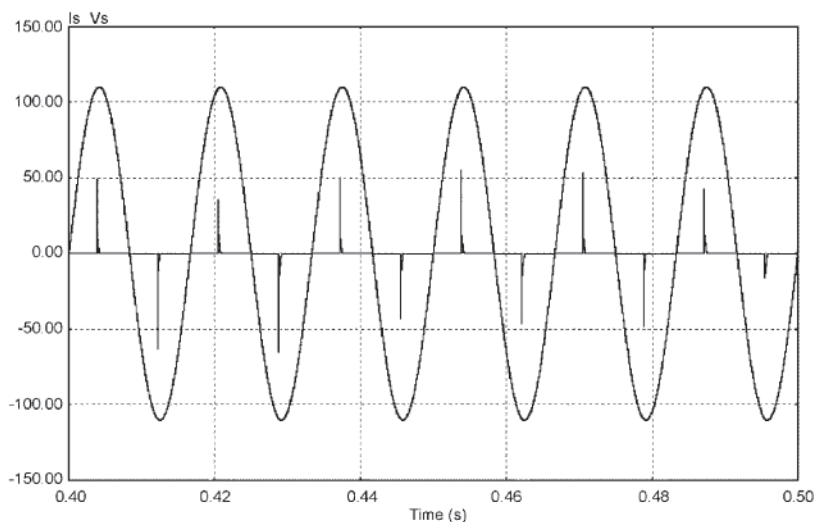


FIGURE 10.8 Input voltage and current of the SRM driver with DBR.

current harmonic distortions. By proper design, it is also effective in achieving good power factors on the line side. These passive PFC circuits, as passive filters, can be added to either the AC or DC side. Generally, they are placed between the diode bridge rectifier mentioned before and DC link capacitor, i.e., on the DC side. Figures 10.9 and 10.10 show the passive PFC circuit and its effect on the supply line and voltage waveforms in simulation results.

As mentioned in the previous section, the nonlinear load power factor depends on displacement power factor too. Generally, a capacitor is added on the AC side to improve DPF. It can be seen from Fig. 10.10 that both phase current and voltage are not changed, but the supply current is very much in phase with the supply voltage. In other words, the power factor is improved considerably. In addition, peak of the input side current is reduced a lot. Thus, THD is also reduced to a great extent.

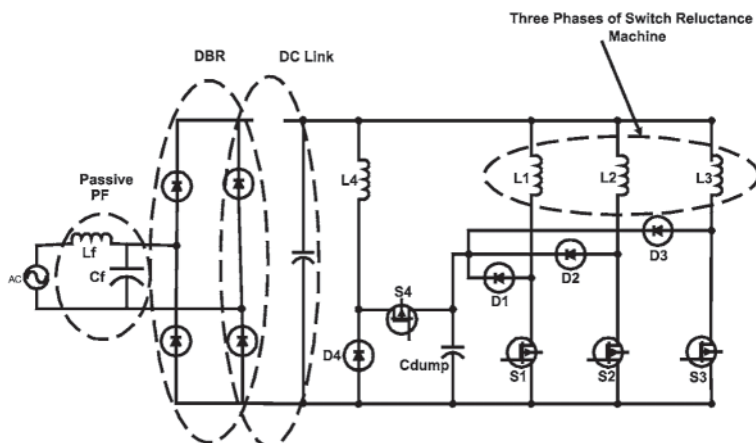


FIGURE 10.9 SRM drive with passive PFC along with DBR at its front end.

It is observed that the power factor with this method is not improved very close to unity. The size of the passive elements, i.e., inductor and capacitor, is also an issue. When more than one conversion stage is involved in the application, relative stability and EMI are the factors to be kept in mind while designing and inserting passive PFC circuits, specifically magnetic components, in the system. However, low cost and simple implementation make this technique attractive to many manufacturers.

Active PFC As this technique involves active switching elements, it is known as active PFC. There are many ways of achieving active power factor correction. A boost converter is the most popular and simplest one. [Figures 10.11](#) and [10.12](#) show the power stage diagram and simulation results for an SRM drive with boost converter.

From the waveforms shown in Fig. 10.12, it is clear that by using a DC/DC boost converter, a power factor of almost unity can be achieved, and the load to the converter appears almost resistive. No current peak is visible in the supply current waveform. Here, a boost converter switch is controlled, keeping output voltage of the converter

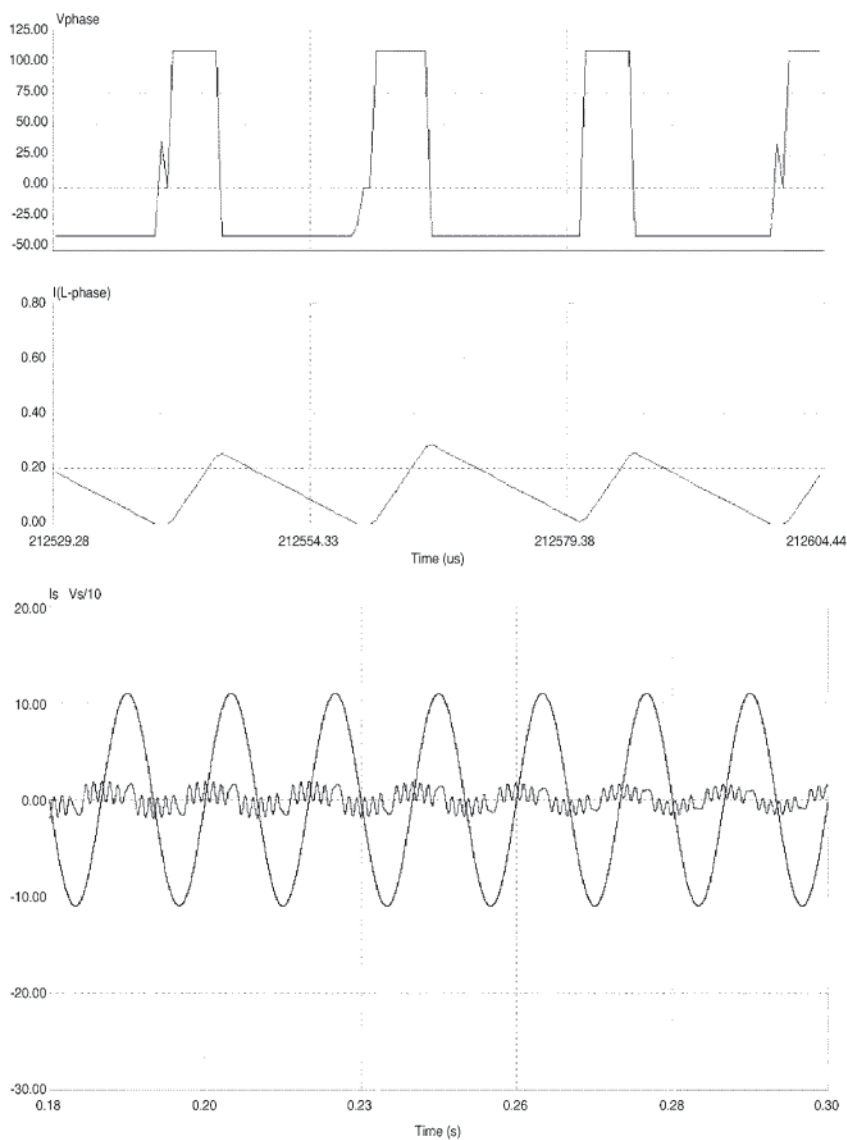


FIGURE 10.10 Phase voltage and current waveforms and supply voltage and current waveforms with passive PFC.

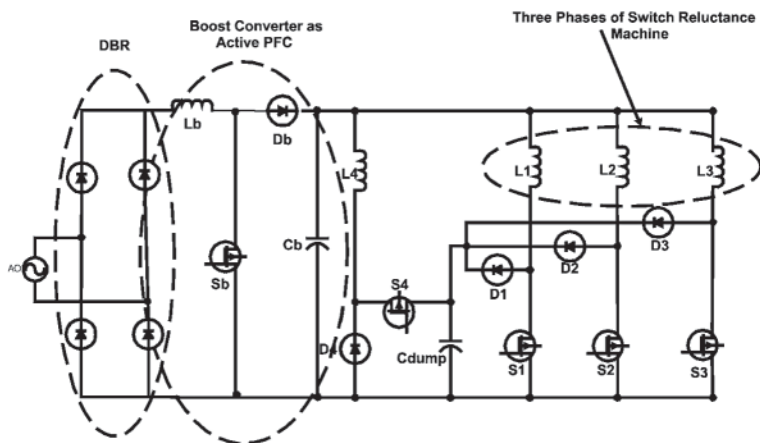


FIGURE 10.11 SRM drive with boost converter along with DBR at its front end.

regulated, but this has nothing to do with controlling the switches of the main SRM drive circuit. During dynamic conditions, it should be observed that the overall system is not becoming unstable. Sometimes all the switches in a system are synchronized to avoid this problem. By modulating the duty cycle of the boost converter switch, the input current can be controlled to track the input voltage. With low distortion and accurate tracking between current and voltage, the power factor obtained from adding a front-end boost converter is typically higher than 0.99, and the input current THD is normally less than 5%. Limitation of the boost converter is that the output voltage should be always greater than the maximum peak supply voltage. To alleviate this problem, another PFC circuit has been developed called the buck-boost converter (Figs. 10.13 and 10.14). This active PFC topology can deliver output voltage both less and greater than the supply voltage depending on the line and load situation. Input voltage can also be tracked by controlling the current in a specific manner. Figures 10.13 and 10.14 show a buck-boost converter at the front end of the SRM drive and its simulation results.

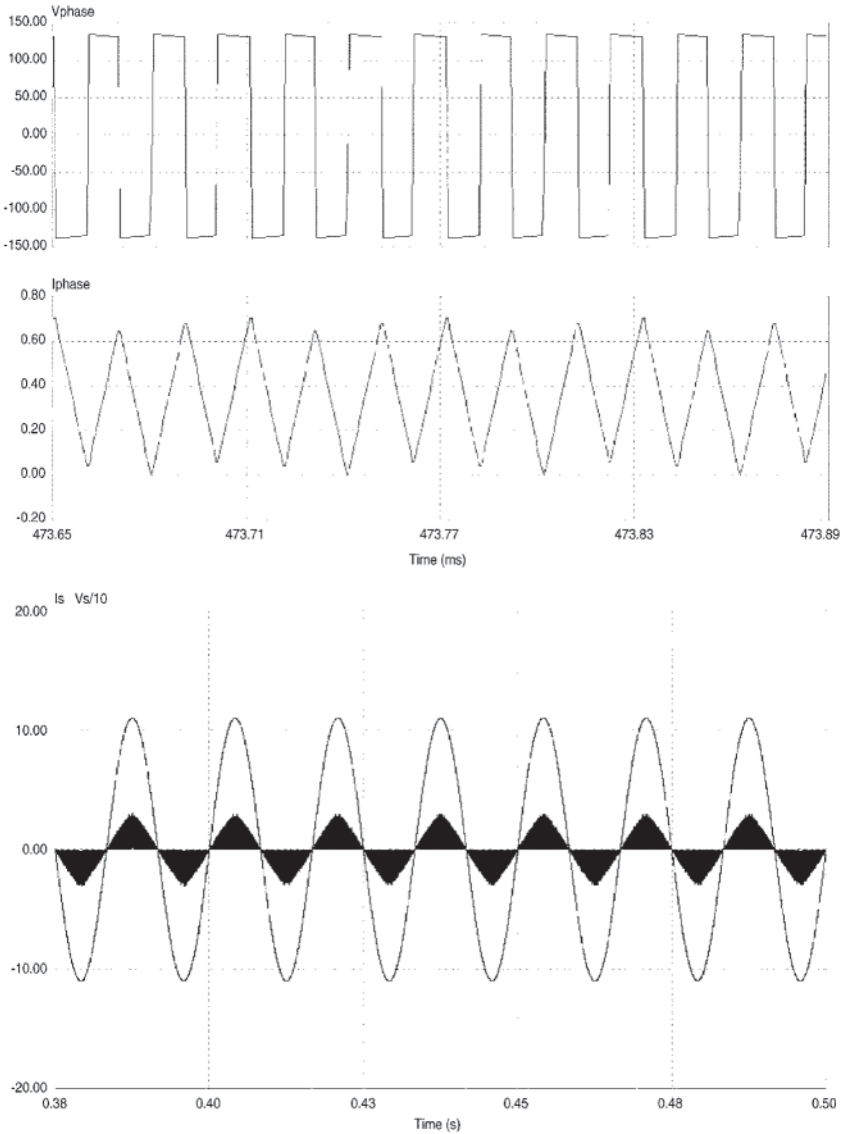


FIGURE 10.12 Phase voltage and current waveforms and supply voltage and current waveforms.

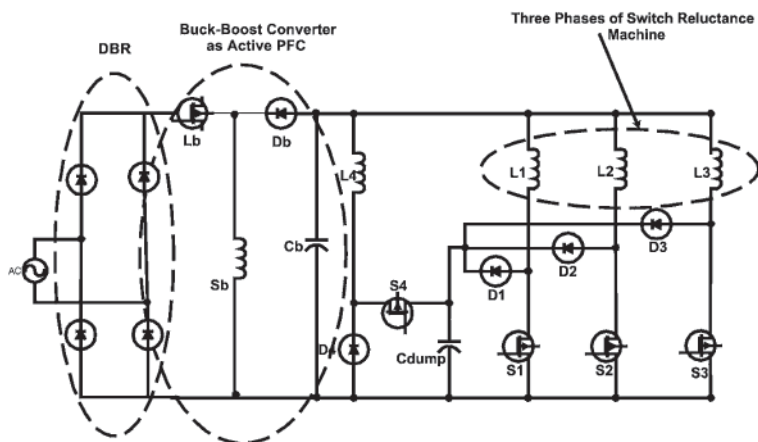


FIGURE 10.13 Buck-boost converter at the front end of the SRM drive.

The boost and buck-boost converters seem to be overcompensating, if satisfying the standards is the only concern. The issue of choosing a passive or active PFC seems to be the tradeoff between cost and effectiveness. The effectiveness means the extent that harmonics are eliminated or reduced, not how well the method complies with the standard. However, with the trend of continuous reduction in semiconductor cost, this barrier will also soon be removed.

Specifically for the SRM, to achieve a high power factor, changes are proposed in the C-dump converter (Fig. 10.15). It has been proved that a very high power factor can be achieved using this SRM drive. This is almost the same C-dump converter discussed earlier with some changes. This also falls in the category of active PFC, or one might say it is a hybrid PFC technique. This is because the switches in the drive circuits are controlled to achieve not only the required phase current and voltage, but also a very high power factor. It can also be seen from the power stage diagram shown in Fig. 10.15 that the mutual inductor just before the DC link capacitor appears almost identical to the passive PFC circuit shown previously in this section.

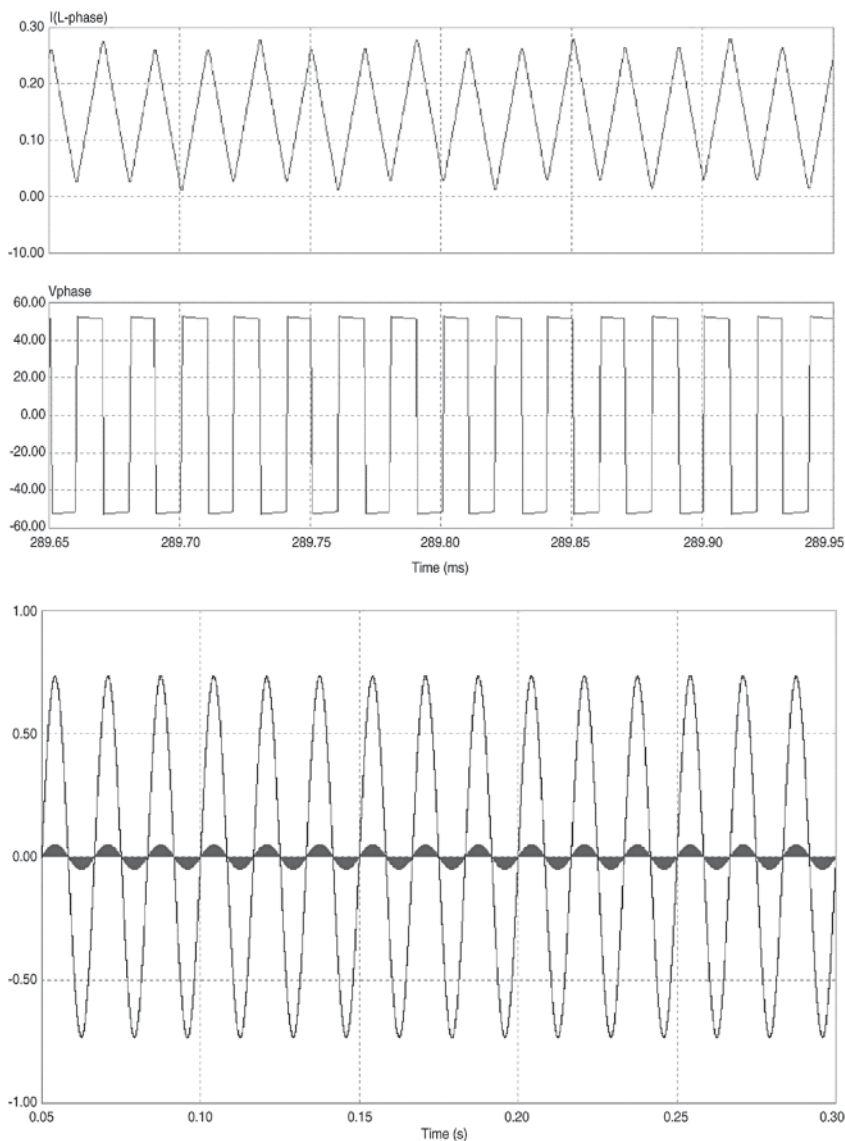


FIGURE 10.14 Phase voltage and current waveforms and supply voltage and current waveforms.

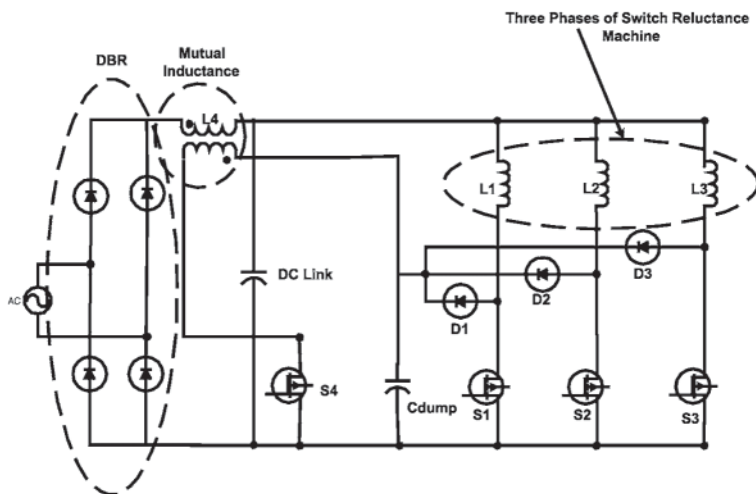


FIGURE 10.15 SRM driver with modified C-dump converter.

Figures 10.16 and 10.17 show the operating modes and simulation results, respectively, of the same converter. A very high power factor without noticeable current distortion can be observed from the simulation results.

Harmonic Injection/External Compensation This method is generally used to filter the harmonics from the line but not to improve the power factor. However, it can be employed for power factor correction. The sizes of passive components increase when they have to remove low harmonic components (source current and voltage are low-frequency signals). This filter is usually configured to plug into an outlet and serve as a plug-in point for 2-to-4 electronic devices. There are three main types of this filter: parallel resonant, series resonant, and series-parallel resonant.

10.3 ACTIVE POWER FILTERS

With the increase of nonlinear loads such as ASDs drawing nonsinusoidal currents, power quality distortion has become a serious

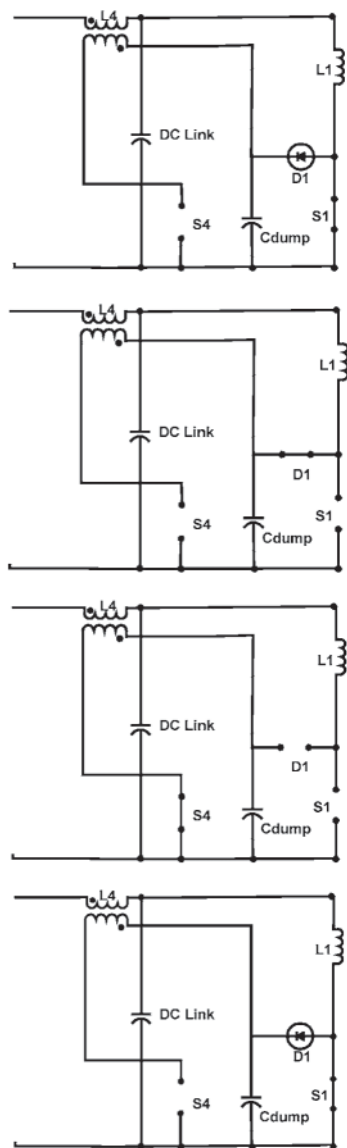


FIGURE 10.16 Operating modes of the modified C-dump converter.

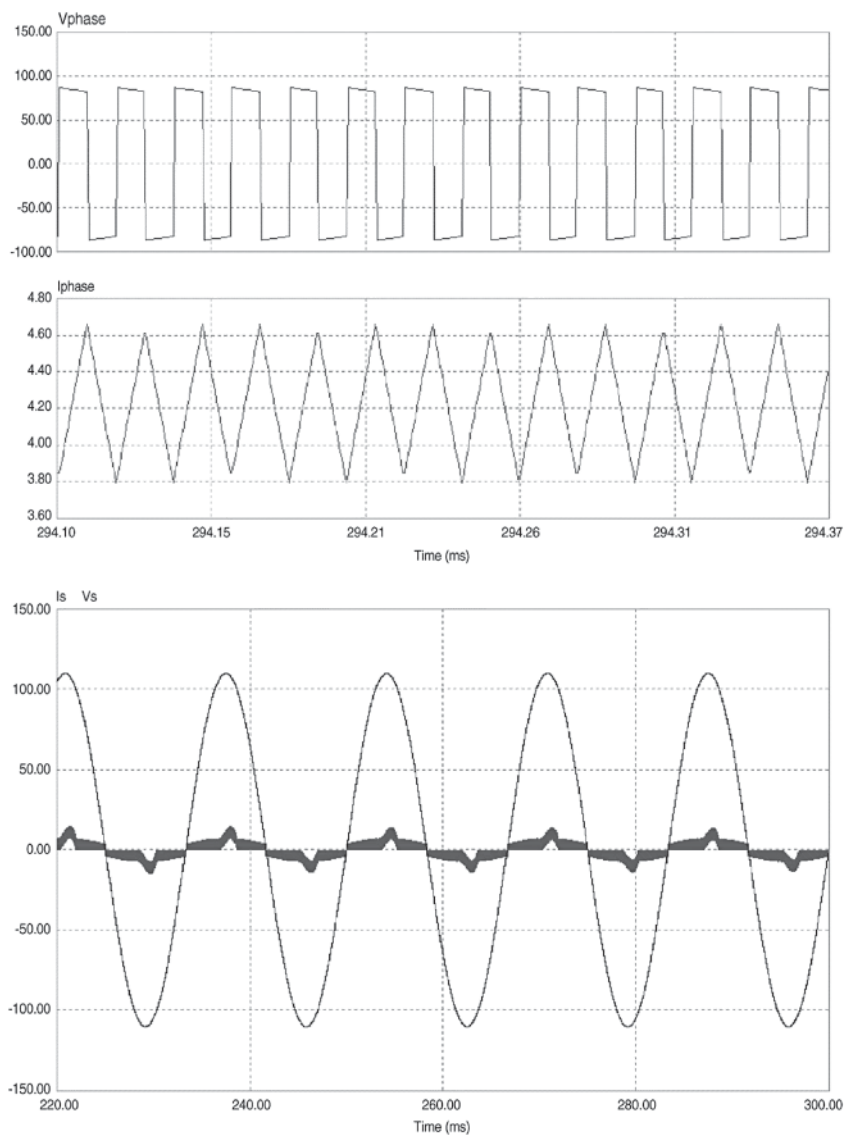


FIGURE 10.17 Phase voltage and current and supply voltage and current waveforms.

problem in power systems. Active filters (AFs) are used for harmonic mitigation as well as reactive power compensation, load balancing, voltage regulation, and voltage flicker compensation. Based on topology, there are two kinds of active filters: current source and voltage source. Current-source active filters (CSAFs) employ an inductor as the DC energy storage device. In voltage-source active filters (VSAFs), a capacitor acts as the energy storage element. VSAFs are cheaper, lighter, and easier to control compared to CSAFs. There are also four types of active filters based on the system configuration.

Current-source active filters use a current-source inductor. This type of energy source is commonly used in shunt-type active filters. Different configurations for this kind of active filter have been developed in forms of low-power, single-phase or high-power, three-phase three-wire or four-wire systems. In the three-phase, four-wire system, load current unbalance can be compensated in addition to current harmonics and reactive current.

In CSAFs, the DC current of the energy storage inductor must be greater than the maximum harmonic of the load (maximum deviation of source current from reference value). If the current of the DC inductor is too small, the inverter cannot do proper compensation. This DC current should not be too much. If the current is too much, excessive loss results in the inductor and inverter; a passive filter cannot cancel switching frequency. There is no need for the DC power supply because an active filter only delivers reactive power and a small amount of fundamental current needed to compensate the AF losses.

A small capacitor is used to protect switches against over-voltages and also to make a low-pass LC filter with the inductor between the active filter and system to suppress switching frequency. For preventing resonance, the resonance frequency of the passive filter must be greater than the highest frequency of harmonics and considerably less than the switching frequency. The control strategy must be well designed to prevent this resonance.

The most dominant type of active filter is the voltage-source inverter (VSI) active filter. Their design has been improved and they have been used for many years; now they are at the commercial

stage. They are lighter, cheaper, and easier to control compared to the current-source inverter (CSI) type. Their losses are less than CSAFs, and they can be made in multilevels and multisteps.

Voltage-source active filters employ a capacitor as the DC energy storage. They are presented in single-phase or three-phase, three-wire or four-wire systems. This kind of active filter is convenient in uninterruptible power supply (UPS) systems. In UPS systems, DC energy storage is available and a DC/AC inverter is also ready. Only a control strategy is needed to convert the UPS to an AF when the source is in normal condition. Different kinds of control techniques are used to control VSAFs. The well-known control techniques are the instantaneous d-q theory, synchronous d-q reference frame method, and synchronous detection method.

In VASF, the DC voltage of the energy storage capacitor must be greater than the maximum line voltage. For proper operation of the active filter, at any instant the voltage of the DC capacitor should be 1.5 times of the line maximum voltage. A linking inductor establishes a link between the filter and system. The AF delivers its current to the system through the inductor. For controllability of AF, this inductor should not be large.

Active filters can also be classified as shunt, series, and hybrid. The most popular type of AF is the shunt type. Shunt AFs can be single-phase or three-phase, VSI or CSI. Shunt AFs are used to compensate the current and voltage harmonics of nonlinear loads, to perform reactive power compensation, and to balance unbalance currents. A shunt AF senses the load current and injects an appropriate current into the system based on its control function. Shunt AFs are currently commercially available.

A shunt AF acts as a current source. The sum of its current and load current is the total current, which flows through the source. Therefore, controlling the output current of an AF can control the source current. Ratings of series and shunt AFs have been compared in some papers. Based on those studies, the shunt AFs has approximately half the switch power rating of series AFs. The peak voltage over switches in series AFs is about one-third the peak voltage over switches in shunt AFs.

Series AFs can also be single-phase or three-phase and employ voltage-source or current-source inverters. Series AFs are mostly used to compensate voltage harmonics produced by nonlinear loads as well as voltage regulation and voltage unbalance compensation.

Series AFs are located in series between source and nonlinear loads. In the presence of source-side impedance, voltage harmonics of the nonlinear load appear at the point of common coupling. Series AFs sense the load-side voltage and produce the harmonic of load voltage in the negative direction and makes the voltage at the point of common coupling free of harmonics.

The main purpose of using a hybrid of active and passive filters is reducing the initial cost of the filter and improving the efficiency. Many configurations and combinations of active and passive filters have been studied and developed. Experimental results of combination series and shunt AFs with shunt passive filters are presented in many papers. Usually, the passive filter is tuned to specific frequency to suppress that frequency, decreasing the power rating of AF. Shunt passive filters should also be high pass to cancel the switching frequency of the AF and high-frequency harmonics. In this case, the switching frequency of the AF will decrease.

Another problem which AFs are faced with is high fundamental current through series AFs and high fundamental voltage across shunt AFs. Paralleling of series AFs with a passive filter can solve high current problems in series AFs. A proper control strategy should be adopted to avoid the possibility of resonance. High voltage across shunt AFs is reduced by putting the shunt AF in series with a passive filter.

Unified power quality conditioners (UPQCs), also known as universal AFs, are ideal devices to improve power quality. A combination of series and shunt AFs forms the UPQC. Series AFs suppress and isolate voltage harmonics, and shunt AFs cancels current harmonics. Usually, the energy storage device is shared between two AFs, either in CSI or VSI. There are two kinds of UPQC. In the first type, a shunt AF is placed near the source and a series AF is placed near the load. The series AF is used to compensate voltage harmonics of the load and the shunt AF is used to compensate residual current

harmonics and improve power factor or to balance the unbalanced load. In the second type, a shunt AF is placed near the load to compensate current harmonics of load, and a series AF is placed near the source to compensate voltage harmonics of the source or regulate the voltage.

In conclusion, IEEE and other international standards are imposing limits on harmonic voltages and currents. Many power electronic circuit designs have been proposed to deal with these standards. Effectiveness of active PFC is normally not a problem, but the cost involved in the additional power electronic circuit could be a major obstacle to acceptance. The simplest power factor correction method is to use passive LC filters to comply with IEC and IEEE standards. Although these passive PFC methods comply with the standards, the problems of EMI, EMC, and size of the passive elements involved must be addressed. Thus, the design of cost-effective power electronic equipment that complies with harmonic standards without introducing side effects or system interaction problems remains an open challenge to power electronic and motor drive engineers.

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